

Supersymmetry with a Chargino NLSP and Gravitino LSP

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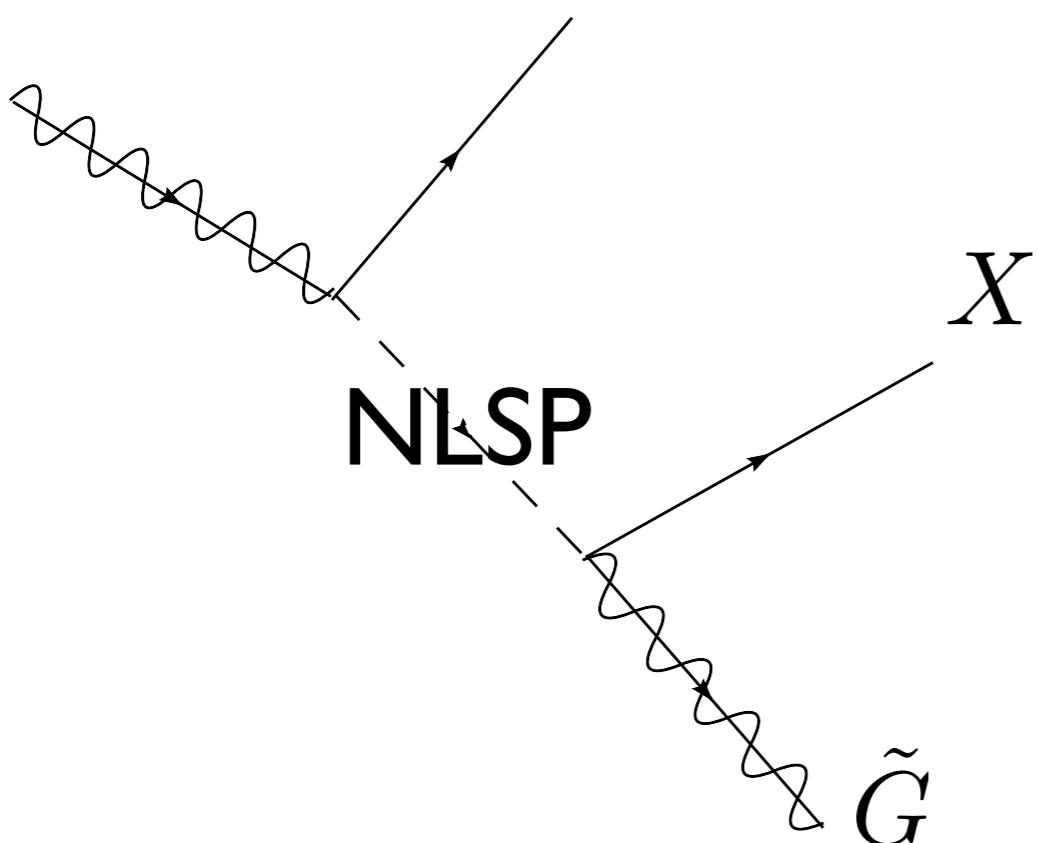
with G. Kribs and T. Roy (U. Oregon)

arXiv:0807.4936 + work in progress

BNL Nov. 6, 2008

For starters...

- Assume gravitino \tilde{G} is the LSP throughout.
→ low ~~SUSY~~ scale
- Then LHC SUSY search strategies are determined by **NLSP** properties



- Γ_{NLSP} determines where decay occurs
- spin, charge, mass of X set expected LHC signals

Important to know all
NLSP possibilities!

Conventional Wisdom

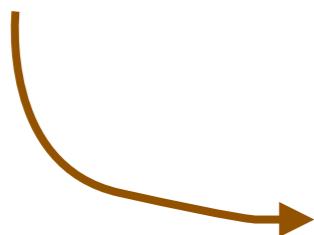
- NLSP can be a:
 - i. charged scalar (slepton, stop)
 - ii. neutral scalar (sneutrino)
 - iii. neutral fermion (neutralino)

- No charged fermion candidates!

$$m_{\chi_0} < m_{\chi^\pm}$$

- Collider Signals: $\gamma\gamma + \text{MET}$
 $\ell^+\ell^- + \text{MET}$

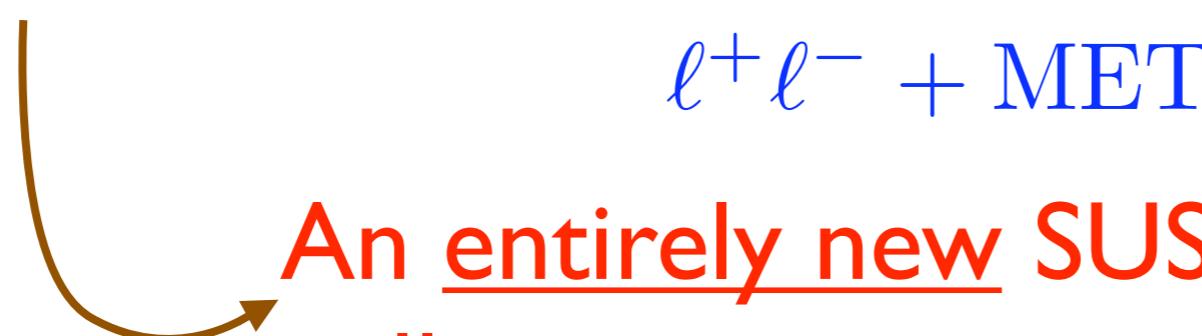
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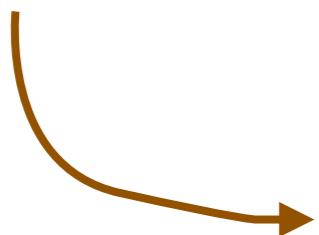
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An entirely new SUSY signal:

all events: $WW + \text{MET} + X$

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R symmetry:

$N = 1$ SUSY has a continuous $U(1)$ symmetry

$$\theta \rightarrow e^{-i\alpha} \theta, \quad \bar{\theta} \rightarrow e^{i\alpha} \bar{\theta}$$

chiral superfield Φ has R-charge n : $\Phi(x, \theta) \rightarrow e^{in\alpha} \Phi(x, e^{-i\alpha} \theta)$

$\mathcal{O}(1)$ components have R-charge: n

$\mathcal{O}(\theta)$ components have R-charge: $n - 1$

$$\mathcal{L} = \int d^2\theta d^2\bar{\theta} K(\Phi, \Phi^\dagger) + \int d^2\theta \mathcal{W}_a \mathcal{W}^a + \int d^2\theta W(\Phi) + h.c.$$

$\downarrow \qquad \downarrow \qquad \downarrow$

$$R_K = 0 \qquad \qquad \qquad R_\lambda = 1 \qquad \qquad \qquad R_W = 2$$

Majorana gaugino masses: $m_{1/2} \lambda_a \lambda^a$

→ break continuous $U(1)_R \rightarrow \mathbb{Z}_2$ ‘R-parity’

.. as do ‘ μ ’-term $\mu H_u H_d$

and ‘A’-terms $a_t H_u \tilde{Q} \tilde{u}_R$

A natural home for Dirac inos: MRSSM

- **MRSSM:** minimal R-symmetric extension of MSSM
(Kribs, Poppitz, Weiner '07)

Lets restore the continuous $U(1)_R$ symmetry

$W'_\alpha = \theta_\alpha \mathcal{D}$, $X = \theta^2 \mathcal{F}$, $R_F, R_D = 0$ introduced as spurions

- Can't have Majorana gaugino masses, so add new adjoint matter to get a Dirac mass with gauginos:

Φ_Y, Φ_W, Φ_c for $U(1)_Y, SU(2)_w, SU(3)_c$

we add, for each gauge group

$$\int d^2\theta \frac{\mathcal{W}'}{M} \mathcal{W}^a \Phi_a \longrightarrow \frac{D}{M} \lambda^a \psi_a \rightarrow m_D \lambda^a \psi_a$$

‘R’-partner

MRSSM

- “ μ ” term replaced by two terms, one for each higgs:

$$W_{MRSSM} \supset \mu_u H_u \textcolor{red}{R_u} + \mu_d H_d \textcolor{red}{R_d} \quad R_H = 0, R_R = 2$$

- F-term SUSY breaking mass terms for squark/sleptons

$$\int d^4\theta \frac{\textcolor{blue}{X} X^\dagger}{M^2} Q^\dagger Q \rightarrow m_Q^2 \tilde{Q}^* \tilde{Q}, \text{ etc. just as in MSSM}$$

- A-terms, L-R sfermion mixing **forbidden by R-symmetry**

$$\int d^2\theta \frac{X}{M} H_u Q U_R \supset \frac{F_X}{M} v_u \tilde{Q} \tilde{u}_R \rightarrow m_{LR}^2 \tilde{Q} \tilde{u}_R$$

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$$R_X = 2, R_H = 0, R_{Q,U} = 1,$$

MRSSM properties:

- Naturally heavy gluinos, no ‘A-terms’, different ‘ μ term’
 ↳ many SUSY flavor/CP problems ameliorated...

(Kribs, Poppitz, Weiner ‘07)

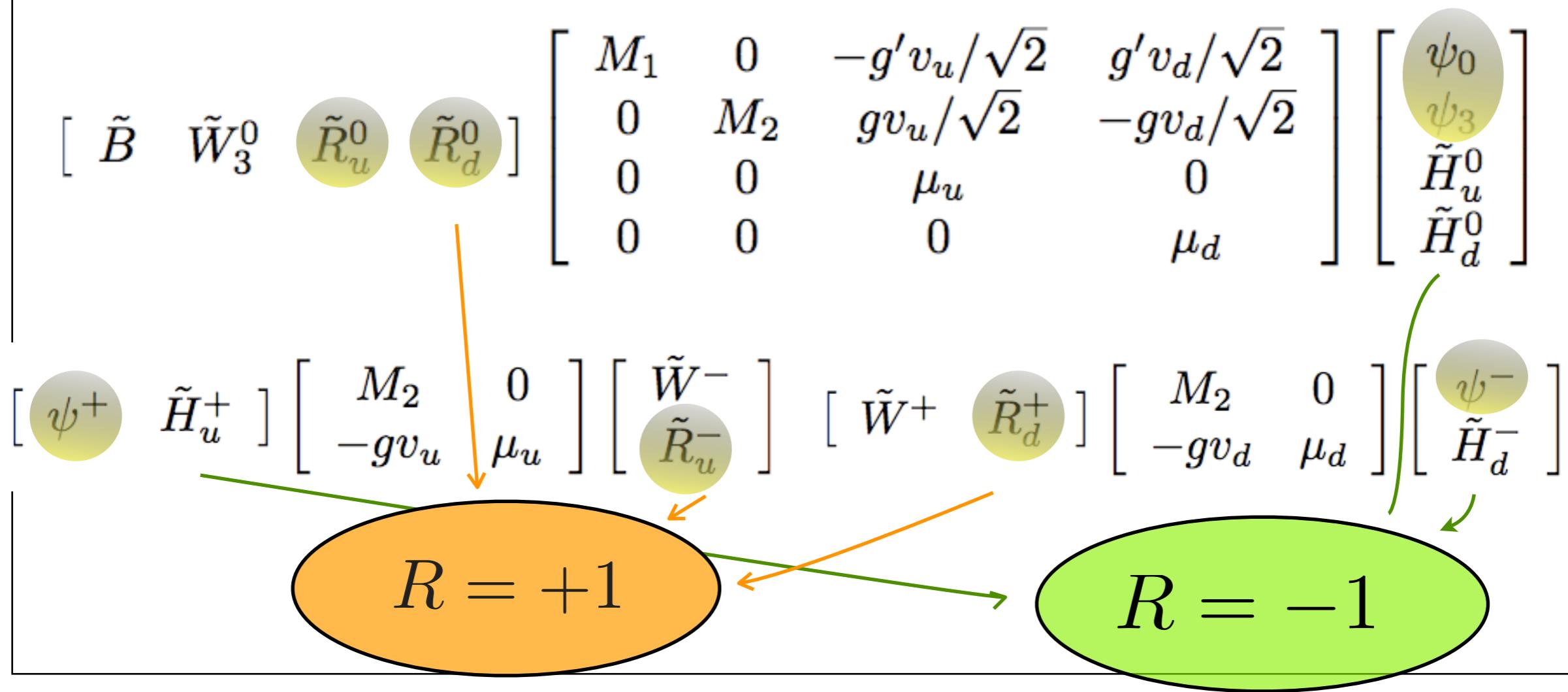
- **All** inos (higgsino + gauginos) are Dirac particles

$$[\tilde{B} \quad \tilde{W}_3^0 \quad \tilde{R}_u^0 \quad \tilde{R}_d^0] \begin{bmatrix} M_1 & 0 & -g'v_u/\sqrt{2} & g'v_d/\sqrt{2} \\ 0 & M_2 & gv_u/\sqrt{2} & -gv_d/\sqrt{2} \\ 0 & 0 & \mu_u & 0 \\ 0 & 0 & 0 & \mu_d \end{bmatrix} \begin{bmatrix} \psi_0 \\ \psi_3 \\ \tilde{H}_u^0 \\ \tilde{H}_d^0 \end{bmatrix}$$

$$[\psi^+ \quad \tilde{H}_u^+] \begin{bmatrix} M_2 & 0 \\ -gv_u & \mu_u \end{bmatrix} \begin{bmatrix} \tilde{W}^- \\ \tilde{R}_u^- \end{bmatrix} [\tilde{W}^+ \quad \tilde{R}_d^+] \begin{bmatrix} M_2 & 0 \\ -gv_d & \mu_d \end{bmatrix} \begin{bmatrix} \psi^- \\ \tilde{H}_d^- \end{bmatrix}$$

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MRSSM vs. MSSM

back in the MSSM... $V_{MSSM} \supset \frac{1}{2} \chi_0^\dagger \textcolor{blue}{M}_{\tilde{\chi}_0} \chi_0 + (\chi^+)^T \textcolor{blue}{M}_{\tilde{\chi}_\pm} \chi^-$

$$\chi_0 = [\tilde{B} \ \tilde{W}_3^0 \ \tilde{H}_d^0 \ \tilde{H}_u^0], \quad \chi_+ = [\tilde{W}^+ \ \tilde{H}_u^+], \quad \chi_- = [\tilde{W}^- \ \tilde{H}_d^-]$$

$$M_{\tilde{\chi}_0} = \begin{bmatrix} M_1 & 0 & -g'v_d/\sqrt{2} & g'v_u/\sqrt{2} \\ 0 & M_2 & gv_d/\sqrt{2} & -gv_u/\sqrt{2} \\ -g'v_d/\sqrt{2} & gv_d/\sqrt{2} & 0 & -\mu \\ g'v_u/\sqrt{2} & -gv_u/\sqrt{2} & -\mu & 0 \end{bmatrix} \quad M_{\tilde{\chi}_\pm} = \begin{bmatrix} M_2 & gv_u \\ gv_d & \mu \end{bmatrix}$$

while in MRSSM

$$V_{MRSSM} \supset \bar{\xi}_0 \textcolor{red}{M}_0 \chi_0 + (\xi^+)^T \textcolor{red}{M}_\pm \chi^-$$

$$\xi_0 = [\tilde{B} \ \tilde{W}_3^0 \ \tilde{R}_u^0 \ \tilde{R}_d^0], \quad \chi_0 = [\psi_0 \ \psi_3 \ \tilde{H}_u^0 \ \tilde{H}_d^0] \quad \xi_+ = [\psi^+ \ \tilde{H}_u^+ \ \tilde{W}^+ \ \tilde{R}_d^+], \quad \chi_- = [\tilde{W}^- \ \tilde{R}_u^- \ \tilde{\psi}^- \ \tilde{H}_d^-]$$

$$M_0 = \begin{bmatrix} M_1 & 0 & -g'v_u/\sqrt{2} & g'v_d/\sqrt{2} \\ 0 & M_2 & gv_u/\sqrt{2} & -gv_d/\sqrt{2} \\ 0 & 0 & \mu_u & 0 \\ 0 & 0 & 0 & \mu_d \end{bmatrix} \quad M_\pm = \begin{bmatrix} M_2 & 0 \\ -gv_u & \mu_u \end{bmatrix}$$

MRSSM mass matrices:

A demonstration

- Set $\mu_u = \mu_d = \mu$: same # parameters as MSSM:
- Take limits $M_1 \rightarrow \infty, \tan \beta \rightarrow \infty$

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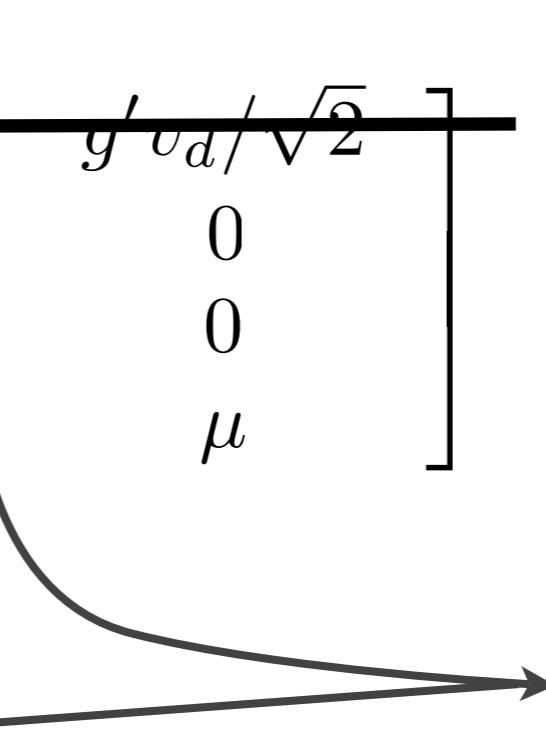
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LARGER off-diagonal
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Simple diagonalization gives:

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LARGER off-diagonal element for charginos

Simple diagonalization gives:

Mass of lightest
chargino

Mass of lightest
neutralino

MRSSM: light chargino limits

- More examples in some common limits:

- ▶ “Higgsino limit”: $\mu \ll M_1, M_2$

$$m_{\tilde{\chi}_{\pm}} - m_{\tilde{\chi}_0} = -\frac{\mu m_W^2}{2M_2^2} + \mathcal{O}\left(\frac{1}{M_2^4}\right)$$

- ▶ “Wino limit”: $M_2 \ll \mu, M_1$

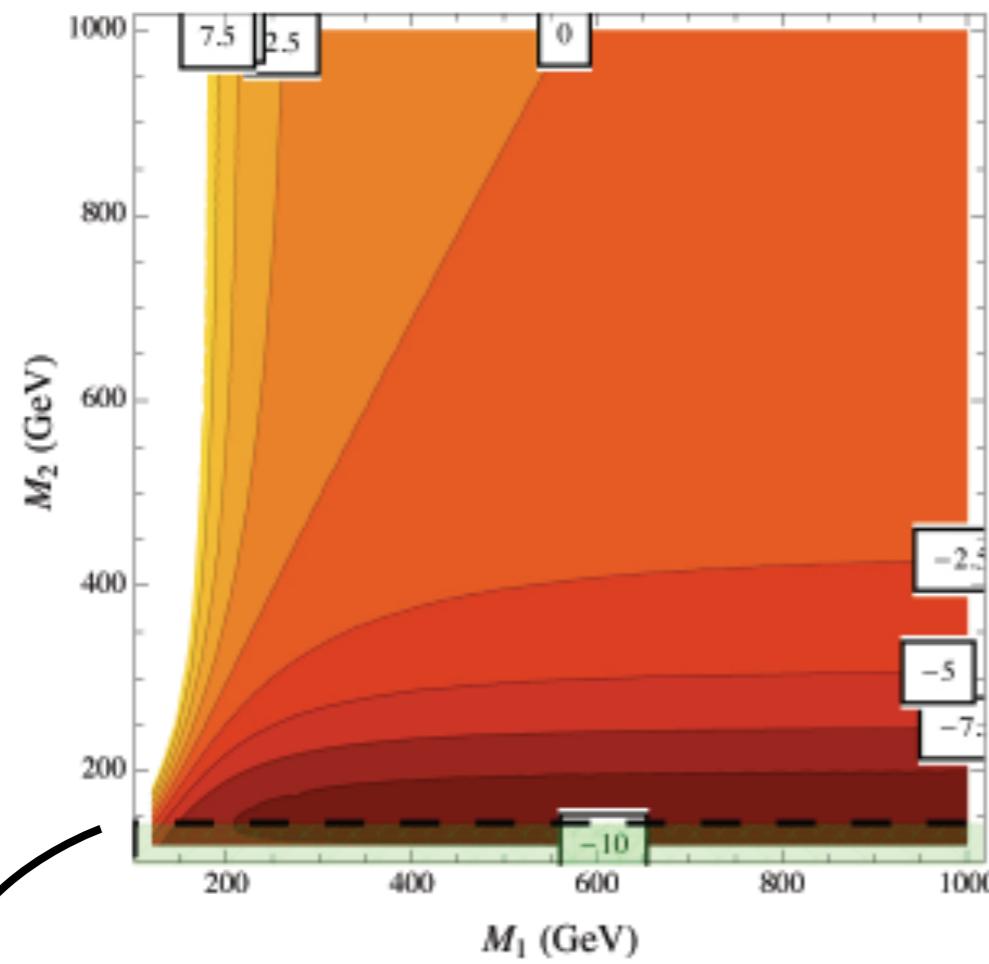
$$m_{\tilde{\chi}_{\pm}} - m_{\tilde{\chi}_0} = -\frac{M_2 m_W^2}{2\mu^2} + \mathcal{O}\left(\frac{1}{\mu^4}\right)$$

chargino is lighter than neutralino!

MRSSM: numerics

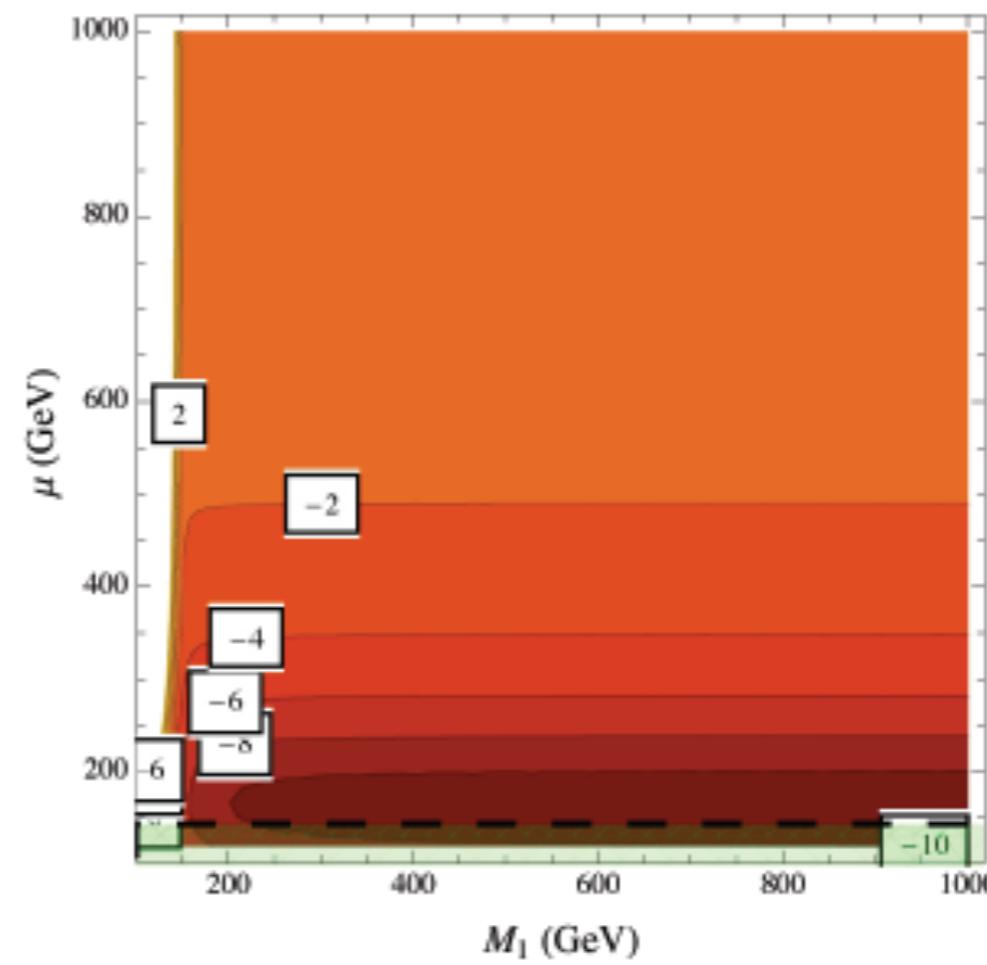
- Numerically, we explore a wider parameter space:

$$\Delta m_\chi = m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}_0} \text{ (GeV)}$$



$$\tan \beta = 10, \mu = 150 \text{ GeV}$$

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$$\tan \beta = 10, M_2 = 150 \text{ GeV}$$

shaded area: $m_{\tilde{\chi}^\pm} < 101 \text{ GeV}$ (LEP II limit)

Widening the parameter space

- Additional couplings are allowed in MRSSM:

$$W \supset \lambda_u H_{u,i} \Phi_w^{ij} R_{u,j} + \lambda_d H_{d,i} \Phi_w^{ij} R_{d,j} \\ + \lambda'_u H_u \Phi_Y R_u + \lambda'_d H_d \Phi_Y R_d$$

consistent with all symmetries

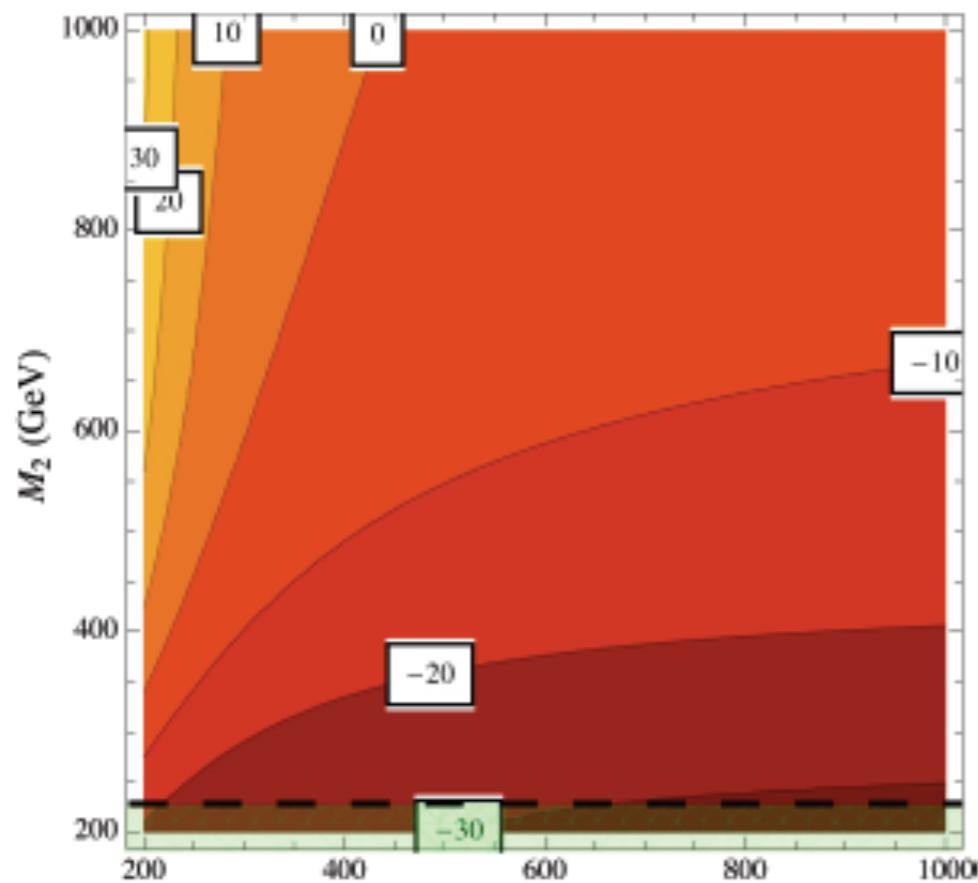
- generates additional mixing in ino-sector

$$\begin{bmatrix} \tilde{B} & \tilde{W}_3^0 & \tilde{R}_u^0 & \tilde{R}_d^0 \end{bmatrix} \begin{bmatrix} M_1 & 0 & -g' v_u / \sqrt{2} & g' v_d / \sqrt{2} \\ 0 & M_2 & g v_u / \sqrt{2} & -g v_d / \sqrt{2} \\ \lambda'_u v_u / \sqrt{2} & -\lambda_u v_u / \sqrt{2} & \mu_u & 0 \\ -\lambda'_d v_d / \sqrt{2} & \lambda_d v_d / \sqrt{2} & 0 & \mu_d \end{bmatrix} \begin{bmatrix} \psi_0 \\ \psi_3 \\ \tilde{H}_u^0 \\ \tilde{H}_d^0 \end{bmatrix}$$

MRSSM continued:

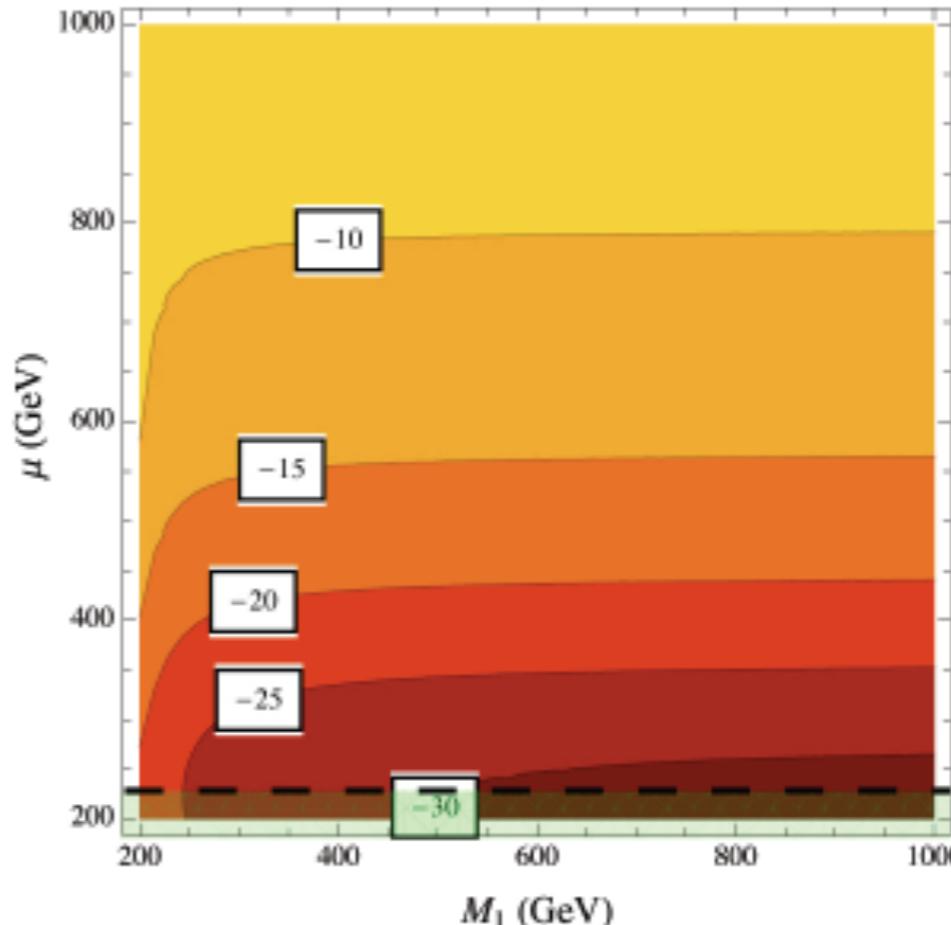
taking, for example: $\lambda_u = \lambda_d = g$, $\lambda'_u = \lambda'_d = g'$

$$\Delta m_\chi = m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}^0} \text{ (GeV)}$$



$$\tan \beta = 10, \mu = 200 \text{ GeV}$$

$$\Delta m_\chi = m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}^0} \text{ (GeV)}$$



$$\tan \beta = 10, M_2 = 200 \text{ GeV}$$

- with extra interactions, much larger mass splittings are possible

$\Delta m_\chi = m_{\tilde{\chi}^0} - m_{\tilde{\chi}^\pm}$ can be **~30 GeV** (tree level)

(~50 GeV possible if we relax $\frac{g'}{g} = \frac{\lambda'}{\lambda}$)

MRSSM comments:

- All results so far are at tree-level, but
radiative corrections to Δm_χ are $\mathcal{O}(\text{GeV})$:
 $\ll \text{MRSSM mass differences}$ (Pierce et al,
hep-ph/9606211)

- Results still valid relaxing $\mu_u = \mu_d$ assumption
ex. Heavy Higgsino limit $\mu_d \neq \mu_u, \mu_d \gg M_1, M_2$

and $M_1, M_2 > \mu_u$

$$\Delta m_\chi \sim -\sin^2 \beta \frac{m_W \lambda v}{2} \left(\frac{1}{M_2} - \frac{\tan \theta \lambda'}{M_1 \lambda} \right) + \dots$$

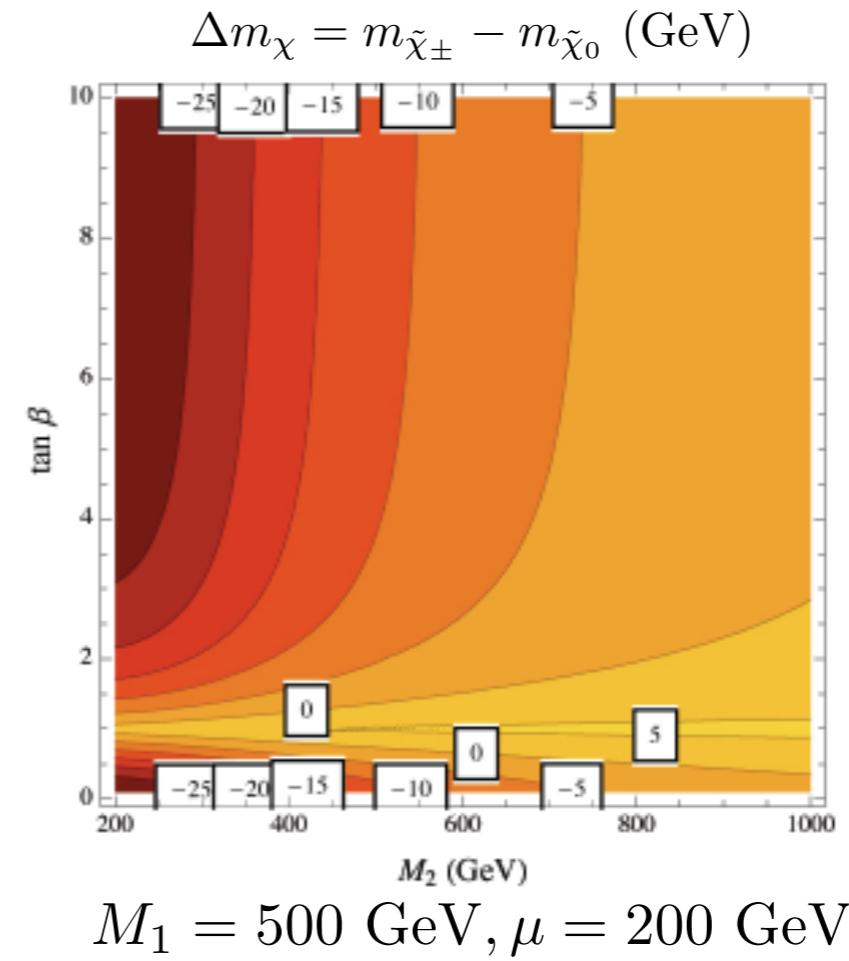
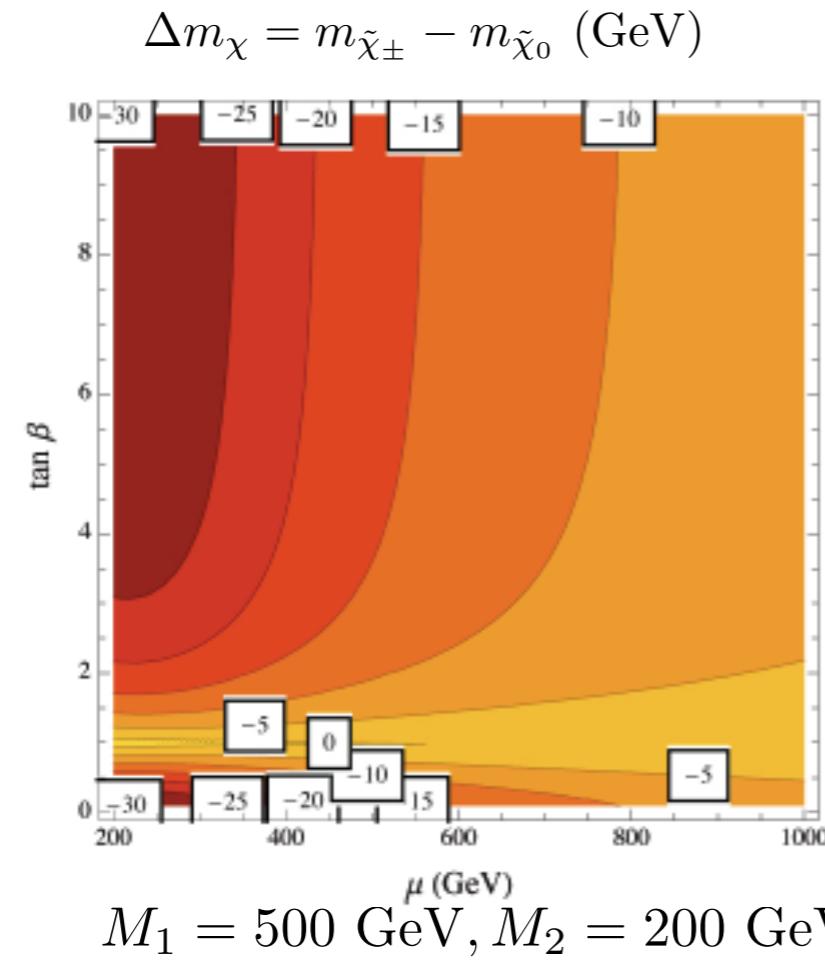
or $M_1, \mu_u > M_2$

$$\Delta m_\chi \sim -\sin^2 \beta \frac{m_W \lambda v}{2\mu_u} + \dots$$

- Leading $\mathcal{O}\left(\frac{1}{M_1}\right)$ corrections are also small

MRSSM comments, cont.

- dependence on $\tan \beta$: biggest mass difference at large values



Do we really need the MRSSM for $m_{\tilde{\chi}_\pm} < m_{\tilde{\chi}_0}$?

Actually, a little-known fact:

Chargino can be lighter
than the neutralino...

...even in the MSSM!

WHERE?

If $M_1, M_2 \gg \mu$

$$m_{\tilde{\chi}_\pm} - m_{\tilde{\chi}_0} = \left[\left(\tan^2 \theta_W \frac{M_2}{M_1} + 1 \right) + \left(\tan^2 \theta_W \frac{M_2}{M_1} - 1 \right) \frac{\mu}{|\mu|} \sin 2\beta \right] \frac{M_W^2}{2M_2} + \mathcal{O}\left(\frac{1}{M_2^2}\right),$$

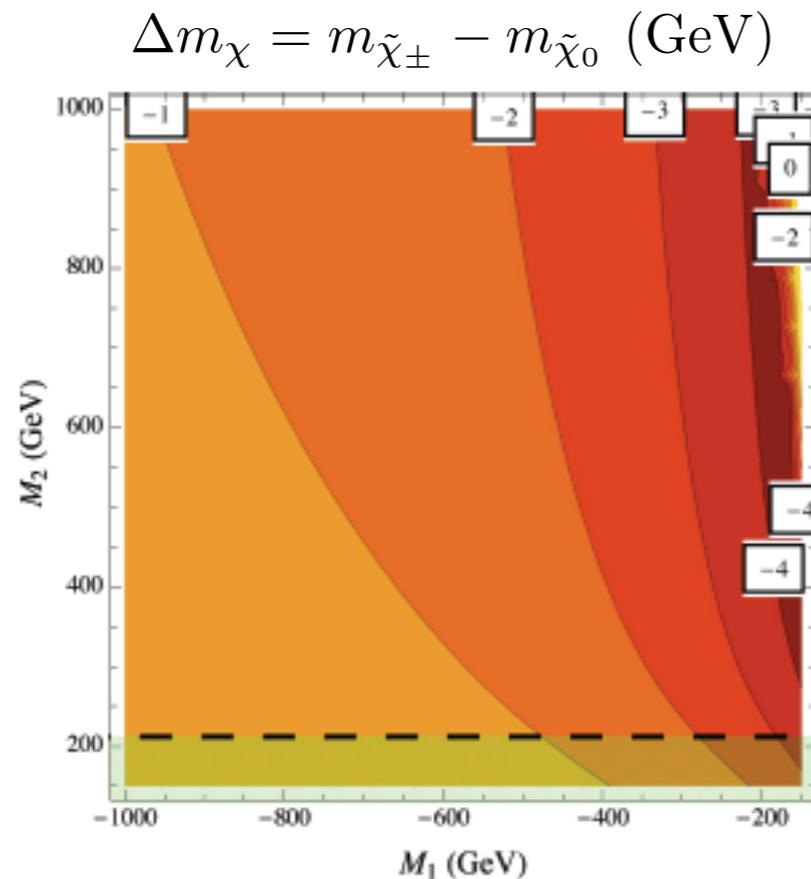
while if $M_1, \mu \gg M_2$

$$m_{\tilde{\chi}_\pm} - m_{\tilde{\chi}_0} = \frac{M_W^2}{\mu^2} \frac{M_W^2}{M_1 - M_2} \tan^2 \theta_W \sin^2 2\beta + \mathcal{O}\left(\frac{1}{\mu^3}\right)$$

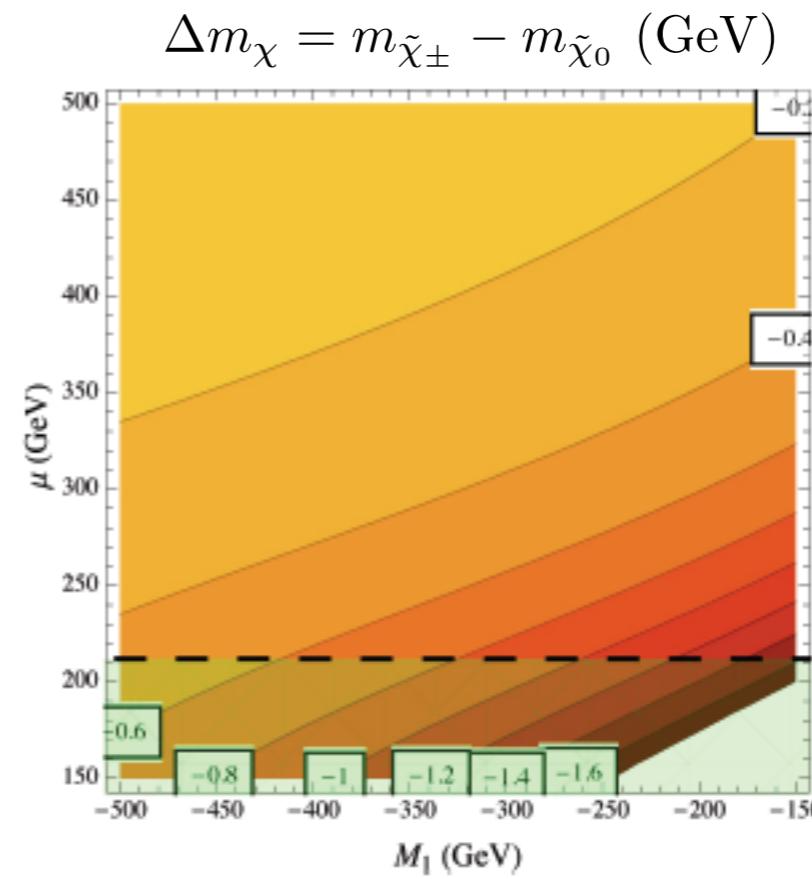
if $\text{sgn}(M_2) = \text{sgn}(M_1)$, as usually assumed, then **lightest chargino is always heavier than the lightest neutralino.**

So, lets consider the scenario $\text{sgn}(M_2) \neq \text{sgn}(M_1)$

MSSM numerics:



$$\mu = 150 \text{ GeV}, \tan \beta = 2$$



$$M_2 = 150 \text{ GeV}, \tan \beta = 2$$

- Although $m_{\chi^\pm} < m_{\chi_0}$ is possible, mass difference is always small
- Radiative corrections important, but unlikely to be larger than \sim few GeV

MSSM continued:

- parameter space where $m_{\chi^\pm} < m_{\chi_0}$ is quite strange.
recall: $sgn(M_2) = -sgn(M_1)$
- MSSM regions of $m_{\chi^\pm} < m_{\chi_0}$:
 - ◆ no gaugino unification
 - ◆ small $\tan \beta \lesssim 5$ necessary
 - ◆ multiple SUSY-breaking fields/messengers needed
 - ◆ +/- phases \longrightarrow why not arbitrary phases?

EDM problems!

LHC signatures

Every SUSY event contains $W^+W^- + \cancel{E}_T$

to determine
charginos as NLSP,
can utilize:

$\left\{ \begin{array}{l} W \rightarrow e, \mu, \tau, \text{jets} \\ m_{\tilde{\chi}} \cong m_W \\ \text{displaced vertices} \end{array} \right.$

If we see a chargino NLSP at the LHC...

- We can rule out any MSSM model with $sgn(M_1) = sgn(M_2)$
(mSUGRA, AMSB, common gaugino mass)
- Additionally, verifying $\Delta m_\chi \gtrapprox 20 \text{ GeV}$ strongly suggests non-MSSM supersymmetry; favoring Dirac inos or extended models (nMSSM)
- Dirac inos: no same-sign lepton signal

Conclusions

- **Charginos are a possibility for NLSP**, opening up a new class of SUSY signals (with gravitino LSP)
- A generic signal when gauginos are **Dirac** -- as in **MRSSM**
- Can also occur in obscure, but interesting regions of MSSM parameter space. $sgn(M_1) \neq sgn(M_2)$
- New signals to be explored:

SUSY signal: $pp \rightarrow W^+W^- + \cancel{E}_T + X$

possibility to rule out many SUSY models at LHC